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Exploring Supersymmetry at a Future Global e^+e^- Linear Collider

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Abstract

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EXPLORING SUPERSYMMETRY AT A FUTURE GLOBAL e^+e^- LINEAR COLLIDER

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This review illustrates by means of sample reactions the potential of a future global e^+e^- Linear Collider (LC) for precision measurements of Supersymmetric particles with emphasis on recent studies and addressing major research directions.

1. Introduction

Many searches for Supersymmetric particles and stringent limits which guide future searches have been set by the LEP experiments in an almost background-free experimental environment. Currently, the Tevatron $p\bar{p}$ collider, taking data at $\sqrt{s} = 2$ TeV, gives important search sensitivity with larger kinematic threshold. When the LHC pp collider starts to operate at $\sqrt{s} = 14$ TeV the kinematic reach will be increased significantly. About 13 years of e^+e^- Linear Collider SUSY studies have been performed with the focus changing from discovery to high-precision analyses. Recent milestones are the TESLA Technical Design Report 2001, the Snowmass 2001 meeting, and the Linear Collider Workshops in Korea (2002) and Amsterdam (2003). This review focuses on new developments for a 500 GeV to 3 TeV LC and includes preliminary results.

2. The Linear Collider Project

2.1. Accelerator

Important accelerator parameters are summarized in Table 1. A future LC is characterized by high luminosity, tunable centre-of-mass energy, low beamstrahlung, beam polarization, additional options for $\gamma\gamma$ and e^-e^- collisions.

2.2. Detector

Extensive and increasing R&D for all sub-detectors is being performed. An example is the development of CCD vertex detectors in the LC Flavour Identification (LCFI) collaboration¹.

Table 1. Accelerator parameters.

Parameter	TESLA		NLC/JLC		CLIC
\sqrt{s} (GeV)	500	800	500	1000	3000
Gradient (MV/m)	23	35	48	48	150
L_{cur} ($10^{34} \text{cm}^{-2} \text{s}^{-1}$)	3.4	5.8	2.0	3.4	10
$L_{\text{int}}/10^7 \text{s}$ (fb^{-1})	340	580	200	340	1000
Beamstrahlung spread (%)	3.2	4.3	4.7	10.2	31

3. Scalar Top Simulation with c-Quark Tagging

In particular, hadronic background can be reduced with c-quark tagging in the reaction $e^+e^- \rightarrow \tilde{t}_1 \tilde{t}_1^* \rightarrow \tilde{\chi}_1^0 c \tilde{\chi}_1^0 \bar{c}$. The expected signal and background rates and resulting sensitivities for the scalar top mass and mixing angle determination are shown in Fig. 1 for benchmark parameters SPS-5 (mSUGRA) $m_0 = 150$ GeV, $m_{1/2} = 300$ GeV, $A_0 = -1000$ GeV, $\tan \beta = 5$, $\mu > 0$, leading to $m_{\tilde{t}_1} = 220.7 \pm 0.6$ GeV and $\cos \theta_{\tilde{t}_1} = 0.537 \pm 0.012$.

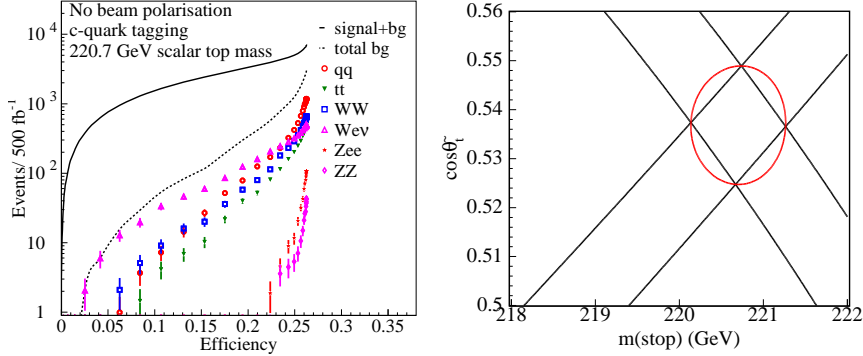


Figure 1. Scalar top quark studies for SPS-5 parameters. Left: expected number of signal and background events with c-quark tagging for unpolarized beams. Right: sensitivity for mass and mixing angle from production cross section precision determinations for $\sqrt{s} = 500$ GeV and a total luminosity of $L = 2 \times 500 \text{ fb}^{-1}$ with $P_{e-} = -0.80$, $P_{e+} = 0.60$ (left-polarization) and $P_{e-} = 0.80$, $P_{e+} = -0.60$ (right-polarization).

4. Complex Phases on Scalar Top and Scalar Bottom Decays

Complex phases in the Higgs potential and soft SUSY breaking terms change the scalar top decay width and branching ratios³, as shown in Fig. 2 for the example of a SPS-4 inspired scenario with $m_{\tilde{t}_1} = 531$ GeV.

5. Scalar Muon Simulation

The reaction $e^+e^- \rightarrow \tilde{\mu}_R^+ \tilde{\mu}_R^- \rightarrow \mu^+ \tilde{\chi}_1^0 \mu^- \tilde{\chi}_1^0$ has been re-investigated⁴ for benchmark parameters (SPS-1a) with $m_{\tilde{\mu}_R} = 145.9$ GeV and $m_{\tilde{\chi}_1^0} = 100$ GeV. The isotropic scalar muon decay leads to a flat energy spectrum. From a fit of this spectrum (end-point method) the following precisions are obtained $m_{\tilde{\mu}_R} = 146.25 \pm 0.15$ GeV and $m_{\tilde{\chi}_1^0} = 99.98 \pm 0.09$ GeV for $\sqrt{s} = 500$ GeV and $L = 400 \text{ fb}^{-1}$.

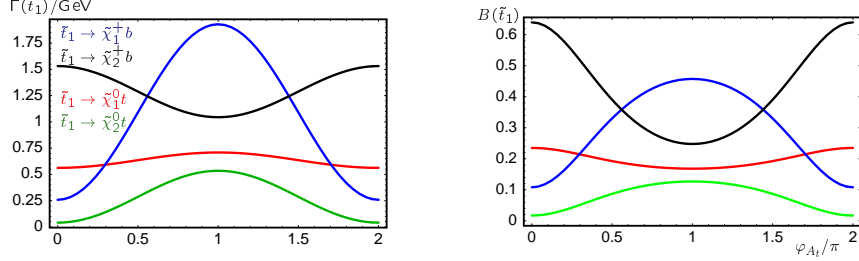


Figure 2. Scalar top decay width and branching ratios as a function of the complex phase of the trilinear coupling of scalar fermion A_f .

6. $\tan\beta$ Sensitivity from Scalar Taus

The polarization of τ leptons from the decay of scalar taus $\tilde{\tau}_1$ depends on $\tan\beta$. The τ polarization can be measured from the shape of the energy spectrum of hadronic τ decays, for example in the reaction $e^+e^- \rightarrow \tilde{\tau}_1^+ \tilde{\tau}_1^- \rightarrow \tilde{\tau}_1^+ \tau^- \tilde{\chi}_1^0 \rightarrow \tilde{\tau}_1^+ \nu_\tau \pi^- \tilde{\chi}_1^0$, as illustrated in Fig. 3⁵.

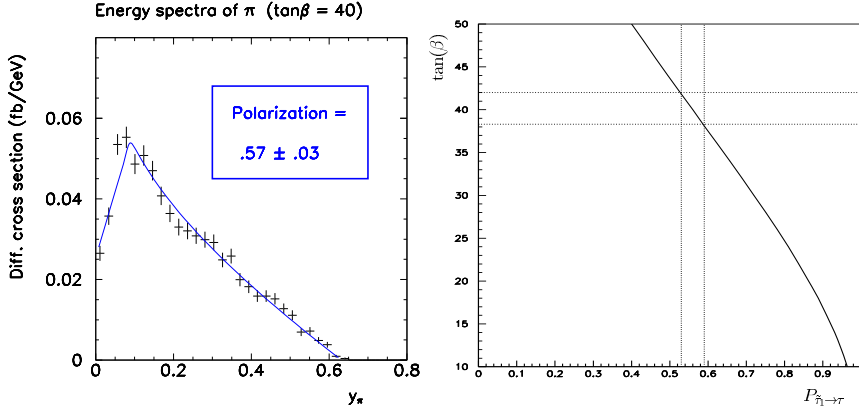


Figure 3. Left: π energy spectrum fit ($y_\pi = 2E_\pi/\sqrt{s}$) determines τ polarization $P = 0.57 \pm 0.03$. Right: resulting sensitivity $\tan\beta = 40 \pm 2$ for $\sqrt{s} = 500$ GeV and $L = 500$ fb $^{-1}$.

7. $\tan\beta$ Sensitivity from Higgs Boson Reactions

Several Higgs boson reactions are particularly sensitive to $\tan\beta$ and excellent sensitivity on $\tan\beta$ from Higgs boson production rate and decay width measurements can be obtained (Fig. 4)⁶.

8. Theoretical and Experimental Precision

As an example for the parameters of SPS-1a (mSUGRA) theoretical precision⁷, and expected experimental precision a) from estimates of combined end-point and centre-of-mass scan methods⁸ and b) from detailed simulations^{9,10} are summarized in Table 2. Some current theoretical uncertainties are much larger than the expected experimental precision.

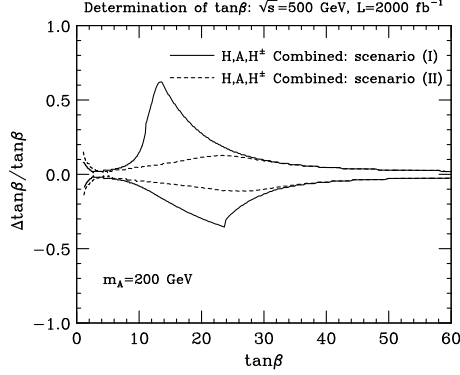


Figure 4. Combined sensitivity on $\tan \beta$ from 1) $e^+e^- \rightarrow b\bar{b} \rightarrow b\bar{b}A \rightarrow b\bar{b}b\bar{b}$ rate; 2) $e^+e^- \rightarrow HA \rightarrow b\bar{b}b\bar{b}$ rate; 3) H, A decay width; 4) $e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t}$ rate; 5) H^+ decay width. Scenario I: no Supersymmetric particle decays, scenario II: Supersymmetric particle decays.

Table 2. Expected theoretical and experimental precision of Supersymmetric particle masses for SPS-1a (mSUGRA) parameters. Δ_{th} : Gaussian error from Isajet 7.64, Softsusy 1.71, Spheno 2.0 and Suspect 2.101 studies. $\Delta_{\text{exp}}^{\text{a}}$: estimated error for a 500 GeV e^+e^- LC with $L = 1000 \text{ fb}^{-1}$. $\Delta_{\text{exp}}^{\text{b}}$: detailed simulations for a 400 GeV e^+e^- LC with $L = 200 \text{ fb}^{-1}$ ($\tilde{\ell}$ and $\tilde{\chi}_1^0$) and for a 500 GeV e^+e^- LC with $L = 500 \text{ fb}^{-1}$ ($\tilde{\nu}_e$).

[GeV]	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{e}_R}$	$m_{\tilde{e}_L}$	$m_{\tilde{\mu}_R}$	$m_{\tilde{\mu}_L}$	$m_{\tilde{\tau}_1}$	$m_{\tilde{\tau}_2}$	$m_{\tilde{\nu}_e}$	$m_{\tilde{\nu}_\tau}$
Δ_{th}	0.3	1.5	1.2	0.6	1.1			1.1	1.1	0.8	1.0
$\Delta_{\text{exp}}^{\text{a}}$	0.07	0.12	0.18	0.02	0.2	0.07	0.51	0.64	1.1	~ 1	—
$\Delta_{\text{exp}}^{\text{b}}$	0.10			0.08		0.17		0.30		0.7	

9. Synergy between the LHC and a LC

For the benchmark parameters of SPS-1a all scalar leptons are in the kinematic reach of a 500 GeV LC and the scalar top quark masses are inaccessible at a LC, but in reach of the LHC sensitivity. Figure 5 shows examples of the potential for combined LC and LHC studies^{11,12}.

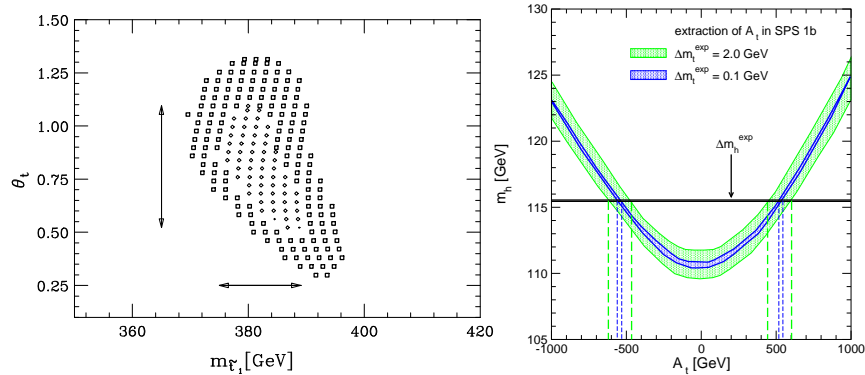


Figure 5. Left: scalar top from LHC and light Supersymmetric particles from LC. LC&LHC give $\Delta m_{\tilde{t}_1} = \pm 7 \text{ GeV}$ and $\Delta \theta_{\tilde{t}} = \pm 0.3$, but no mass and mixing sensitivity can be obtained from the LHC alone. Right: trilinear coupling precision $\Delta A_t = \pm 20 \text{ GeV}$ when in addition to the LHC measurements (light-shaded band), precise top mass measurements from a LC (dark-shaded band) are used.

10. Distinguishing Supersymmetry Breaking Models

At a future LC different Supersymmetry breaking models could be distinguished by their characteristic signatures. For example in Anomaly Mediated Supersymmetry Breaking (AMSB) models, which predict small $\Delta m = m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0}$ values, the reaction $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- (\gamma_{\text{ISR}})$ has been studied¹³. In the decay mode $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \pi^+$ this analysis is based on tagging of initial-state radiation photons γ_{ISR} . A fit of the π spectrum $E_\pi \approx \Delta m$ gives $\Delta m = 0.413 \pm 0.017$ GeV for $\sqrt{s} = 500$ GeV and $L = 500 \text{ fb}^{-1}$.

Another example is the Gauge Mediated Symmetry Breaking (GMSB) model with the reaction $e^- \gamma \rightarrow \tilde{\chi}_1^0 \tilde{e}_R^- \rightarrow \tilde{e}_R^- e^- \tilde{e}_R^- \rightarrow e^- e^- e^- \tilde{G} \tilde{G}$ ¹⁴, where a triple electron and missing energy signature is expected in an $e^- \gamma$ collider. In this model the lightest Supersymmetric particle is the gravitino \tilde{G} .

11. $\gamma\gamma$ Collider and R-Parity Violation

The option in the LC project of photon collisions opens new fields of research. For example, in a photon-photon collider, scalar neutrinos could be produced via the reaction $\gamma\gamma \rightarrow f\bar{f}\tilde{\nu} \rightarrow f\bar{f}f\bar{f}$ which is almost free of Standard Model background in the $\mu^+\mu^-\tau^+\tau^-$ final state¹⁵. The Feynman graphs and expected production cross sections are shown in Fig. 6.

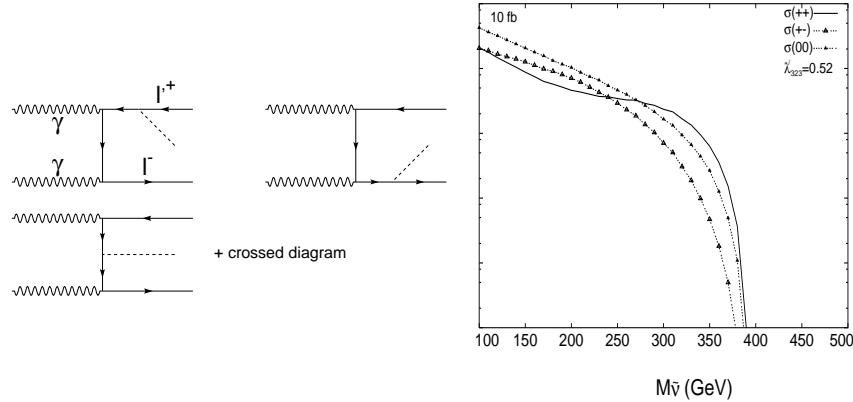


Figure 6. Left: $\gamma\gamma \rightarrow f\bar{f}\tilde{\nu}$ graphs, $\tilde{\nu}$ (dotted line). Right: $\sigma \times BR(\tilde{\nu} \rightarrow f\bar{f})$ for different beam polarization states.

12. e^-e^- Collider

Another option in the LC project, e^-e^- collisions, allows precision measurements beyond the sensitivity of an e^+e^- LC. Figure 7 shows as an example the production cross section for $e^-e^- \rightarrow \tilde{e}_R^- \tilde{e}_R^- \rightarrow e^-e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$ and the precision of the mass determination of scalar electrons. With a luminosity of only 10 fb^{-1} the expected precision is about 20 MeV¹⁶.

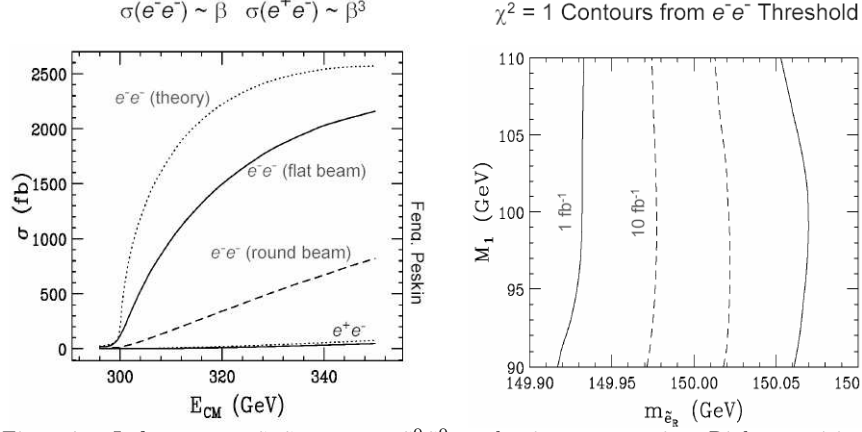


Figure 7. Left: $e^-e^- \rightarrow \tilde{e}_R^- \tilde{e}_R^- \rightarrow e^-e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$ production cross section. Right: precision of the mass determination of scalar electrons for $\sqrt{s} = 300$ GeV and $P_{e^-} = 0.8$.

13. CLIC 3 TeV

The CLIC project aims at higher centre-of-mass energies. An example of the expected precision on the masses of scalar muons, and neutralinos $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ from the reaction $e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow \mu^- \tilde{\mu}_R^+ \mu^+ \tilde{\mu}_R^- \rightarrow \mu^- \mu^+ \tilde{\chi}_1^0 \mu^+ \mu^- \tilde{\chi}_1^0$ is given in Fig. 8¹⁷.

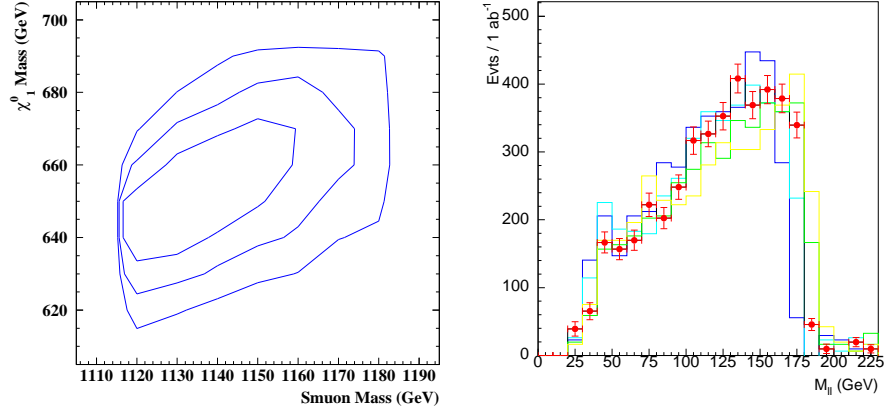


Figure 8. Left: reconstructed scalar muon and neutralino $\tilde{\chi}_1^0$ masses. Right: $\tilde{\chi}_2^0$ mass from the muon mass spectrum in one hemisphere $\Delta m_{\tilde{\chi}_2^0}/m_{\tilde{\chi}_2^0} = 1.7\%$.

14. Conclusions

Exploring Supersymmetry at a future linear collider is a very active field of research with many new ideas and new directions. These studies also contribute to the detector design, for example with c-quark tagging as a benchmark for vertex detectors.

After a first discovery at the Tevatron or the LHC and initial precision measurements, the production and decay modes of many Supersymmetric particles will be measured with very high precision in the first phase of a LC. The Linear Collider will probe the underlying production and decay mechanisms. Detailed studies of several benchmark scenarios have been performed and Supersymmetry breaking models like mSUGRA, AMSM, or GMSB will be distinguished for a wide range of parameters. Combined LC and LHC physics will expand the precision measurements and allow for important consistency checks of the model. The physics case for a future LC is established and the High-Energy-Physics community is ready to embark on the construction of the future global LC.

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